A study of translator length in a tubular linear electrical machine designed for use in a linear combustion joule engine

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***Abstract*— the aim of this paper is to investigate the integration of a tubular linear electrical machine with a linear free-piston combustion engine in order to create a single integrated free piston engine generator. The performance of a long and short translator electrical machine is discussed. To simulate the dynamic performance of the overall system, an integrated thermodynamic, mechanical and electromagnetic model is required. LMS Amesim software is used to model the thermodynamic engine and electromechanical finite element analysis is used for the electrical machine. The performance of electrical machines with varying translator length is investigated. The performance of such a tubular generator is demonstrated by measurements on a 7-pole/6-slot prototype machine. In terms of cost and performance, the short translator generator design was proved to be better than the long translator generator design based on the dynamic simulation results of the system.**

Keywords— Linear Generator, Free Piston Engine, Alternative Energy

I. Introduction

A direct drive free piston engine generator is a special type of combustion engine, representing a new approach to the conversion of the chemical energy of hydrocarbon fuel into electrical energy. Unlike conventional engines, this type of engine does not use a crankshaft, thus, the piston motion is determined solely by the forces that act on it, i.e. that due to the cylinder pressure force and generator force [1, 2]. Electrical energy is hence generated directly by the linear movement of pistons. This new type of energy conversion device has many potential advantages like high efficiency, high power density, few moving parts, multi-fuel possibility and fast transient response, which make it a promising candidate power device for high efficiency series hybrid vehicle [3, 4]. It requires the development of bespoke linear machines, such as those shown in Fig. 1 developed by the authors [5-8] and other works [9, 10]. The PM linear tubular electrical machine has been shown as suitable for this application.

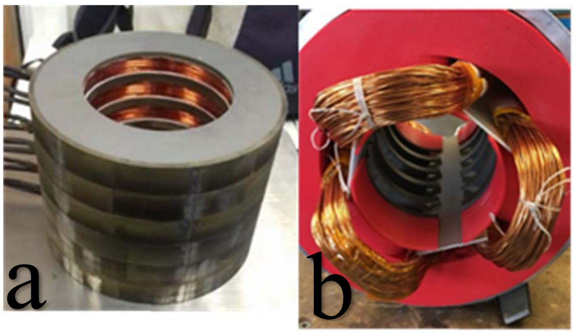

Fig. 1: The stators of two cylindrical machines developed for the free piston engine: (a) Permanent magnet synchronous and (b) transverse flux [5, 8].

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II. Electrical Machine Topology

The permanent magnet linear generator consists of two components: a stator and a translator. The stator has three phase armature windings encased in a back iron, separated by laminated teeth. The translator is the moving portion of the machine which is made up of permanent magnets separated by pole pieces and the shaft to which they are mounted.

In this paper, the tubular linear synchronous permanent magnet machine with axially magnetized permanent magnets mounted on translator is studied and the stator of which was shown in Fig. 1(a). The active electromagnetic area is composed of a three phase, six slot /seven pole combination and equipped with a modular stator winding in which circumferential coils of each phase are located adjacent to each other. This has been shown to give a higher force capability compared with conventional winding can be achieved [15-17]. In a previous study [8], the authors have investigated translators with radial, axial and Halbach permanent magnets within the volumetric constraints of the system, and found axially magnetized magnets offered the best performance.

All previous studies assumed a translator length greater than the stator length and were designed assuming a fixed velocity profile. In this paper, the effect of translator length on overall system performance will be investigated by presenting and using a multi-physics model of the system. Fig. 2 shows two electrical machine configurations with the same electromagnetic active area and shear stress, but alternative translator lengths. The long translator generator design manufacturing was described in [14]. The two machines have identical dimensions and parameters, i.e. number of turns, tooth, slot, poles and diameters have been used for both designs. The translator length was halved, and the stator length doubled in the short translator generator design, which in turn, doubles the stator mass and impedance and halves the translator mass in order to investigate the effect of change in the moving mass on system performance.

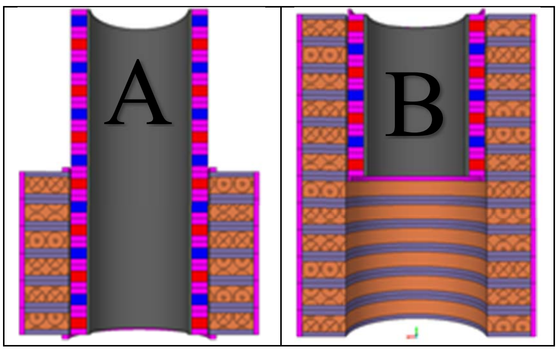

Fig. 2: Generator configurations. A) Base line Long translator, B) short translator.

III. ELECTRICAL MACHINE MODELING

The linear translator has permanent magnets (PMs) mounted with alternating polarity. This translator is then moved sinusoidally, Fig. 3. The amplitude associated with this motion is denoted h and the angular frequency of the translator motion is ω_m . Then the position of the translator, x, can be written as:

$$x(t) = h.\sin(\omega_m t) \tag{1}$$

Then the corresponding translator speed may be written as,

$$\frac{dx}{dt} = \dot{x}(t) = h.\omega_m.\cos(\omega_m t) \tag{2}$$

Assuming that the flux $\emptyset$ in the air-gap varies sinusoidally with position, then the flux a function of position may be written as,

$$\emptyset(x) = \emptyset_m * \sin(\frac{\pi x}{\tau_{pp}}) \tag{3}$$

$$\frac{d\emptyset}{dx} = \emptyset_m \frac{\pi}{\tau_{pp}} \cos(\frac{\pi x}{\tau_{pp}}) \tag{4}$$

Based on Faraday's law, Electro-motive force (EMF) of one phase can be calculated from the flux linkage in the coils. In simple words, EMF can be obtained by derivation of flux with respect to time. EMF is defined as:

$$EMF = -N * \frac{d\emptyset}{dt}, \text{[Volts]} \tag{5}$$

Where:

$\emptyset$: $flux\ linkage\ that\ varies\ with\ translator\ position$

N: $number\ of\ turns\ per\ phase$

$$EMF = N\frac{d\emptyset}{dt} = \frac{d\emptyset}{dx} * \frac{dx}{dt} = N\emptyset_m \frac{\pi}{\tau_{pp}} * velocity * \cos(\frac{\pi x}{\tau_{pp}}) \tag{6}$$

$$\tau_{pp} = \frac{L_{active}}{N_{translator}} \tag{7}$$

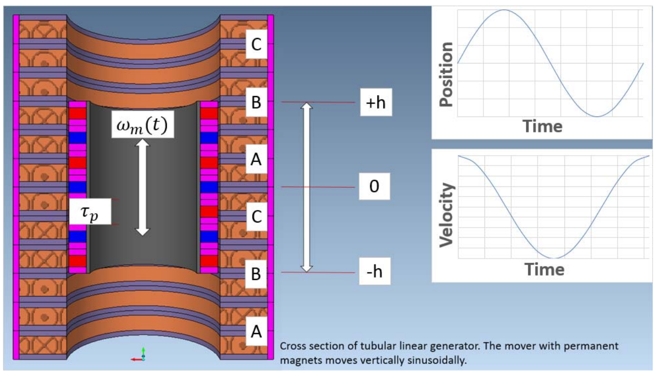

Fig. 3: Cross section of linear generator with short translator. The translator moves sinusoidally.

IV. EQUIVALENT CIRCUIT OF THE SINGLE PHASE GENERATOR

The ultimate goal of this paper is to examine the electrical output power of the integrated linear engine-generator combination. Thus, it is important to examine the electrical model of generator. Fig. 4 shows the equivalent circuit diagram of the generator per phase. Eelectrical output power can be obtained based on Kirchhoff's voltage rule from electric equivalent circuit of generator per phase.

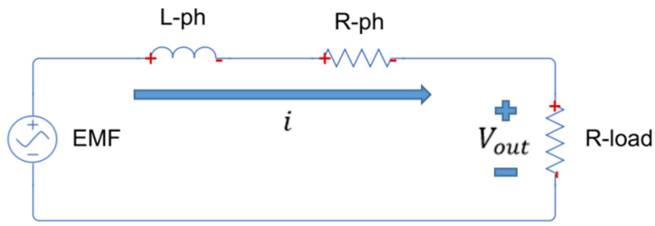

Fig. 4: Equivalent per phase circuit diagram.

The terminal voltage V_{out} for a phase can be defined as:

$$V_{out} = EMF - R * i - L\frac{di}{dt} \tag{8}$$

Where R is phase resistance, i is the phase current and L is phase inductance.

In these equations the values of inductance and flux linkage are extracted from finite element analysis performed on the electrical machine. It is interesting to note that, the accuracy of the existing electric model is based on the accuracy of FEA.

By obtaining the peak flux linkage value from FEA, then the back EMF can be calculated. Thus, the current in the electric model of Fig. 4 can be obtained by knowing the value of winding resistance of each phase. By knowing the current, voltage and power can be calculated as follows:

$$\text{I} = \frac{\frac{\text{EMF}}{\sqrt{2}}}{\text{R}_{\text{ph}}+\text{R}_{\text{load}}+\text{j}\omega\text{l}} \tag{9}$$

$$V_{out} = R_{load} * i \tag{10}$$

$$P_{electrical\ output} = V_{out} * i \tag{11}$$

The variable velocity associated with reciprocating machines gives a variable electric frequency, hence ω_m is not constant. The value of current can be obtained in Matlab/Simulink by solving the differential equation.

$$\frac{di}{dt} = \frac{1}{L}[EMF - R * i] \tag{12}$$

In this work, the generator is modelled by the equivalent circuit of Fig. 2 to calculate current and a series of look up tables to find instantaneous force. This is coupled to the forces from the thermodynamic model and used to find the position and velocity for the next time step, as described in the next section.

V. FREE-PISTON ENGINE-GENERATOR PROTOTYPE AT NEWCASTLE UNIVERSITY

Fig. 5 shows a photograph of the full system on test at Newcastle University. It is comprised of a compressor cylinder (left), a linear motor/generator (middle), an expansion cylinder (right) and an external reactor (above) for combustion of air and fuel. In addition, two double-acting free-pistons are placed in the compressor and the expander cylinders respectively, which separates the cylinders into two opposite chambers. It is also possible to use waste heat, renewable energy or even any fuel combustion in external reactor for driving the piston in the expander cylinder [11].

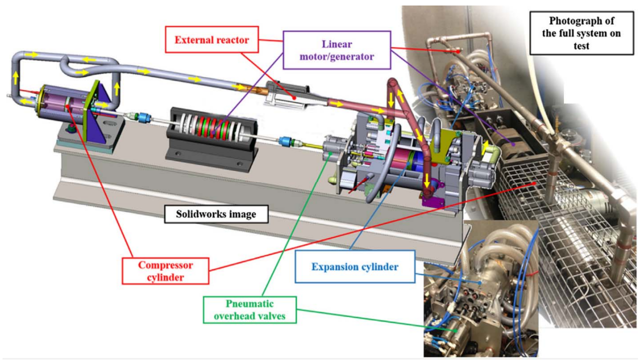

Fig. 5: Concept of LJEG prototype at Newcastle University [11].

VI. PRINCIPLE OF OPERATION

It should be mentioned that, the combustion on this structure occurs outside of the cylinder, in an external reactor, reducing the thermal issues related to the combustion of fuel and air mixture, hence the risks of demagnetisation of PMs or damaging the winding and isolation is reduced. It is an open system, and the exhaust gas after the expander would be high-pressure, high temperature gas. The air is compressed in the compressor with a double-acting free piston and several poppet valves for intake and discharge; the compression of the air results in a high pressure, high temperature air, which is fed into an external reactor. Simultaneously, the fuel is fed into the combustor and reacts with the air to produce heat and high pressure gas. The expander reduces the pressure and temperature by expanding the working fluid and this expansion is used to drive the linear generator and the compressor back and force [11, 12].

VII. INTEGRATED MODELLING

Fig. 6 shows a diagram of modelling of Free-Piston Engine-Generator system. As it is clear, there is a link between engine, generator and load. In addition, it should be mentioned that any variation in load would affect the generator and engine performance. Based on the diagram which is shown in Fig. 6, a fully integrated models of electrical machine model with thermodynamic cycle model of free piston engine can be accomplished in LMS Amesim software in order to investigate the overall system performance and also investigating the effect of translator mass on output electrical power.

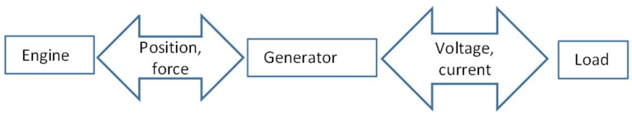

Fig. 6: Diagram of modelling of Free-Piston Engine-Generator.

A dynamic model of the linear joule engine is developed in LMS Amesim software, based on steady state balanced force equation of reciprocating system based on [13]. According to Newton's second law of motion, electromagnetic force acting on the translator and pressure forces in each cylinder is equal to acceleration multiplied by total moving mass.

$$\sum F = a * M_m \tag{13}$$

$$\sum F_{expander} + F_{generator} + F_{compressor} = a * M_m \tag{14}$$

Where $F_{expander}$ is driving force in expander cylinder due to combustion (expander hot cylinder), $F_{compressor}$ is reacting force due to driving force in compressor cylinder (compressing cold cylinder) and $F_{generator}$ is linear generator reacting force, see Fig. 5. In this study the electromagnetic force of two generators are roughly the same, see Fig. 9, however with different moving mass, in order to observe the moving mass effect on the system performance.

VIII. DESIGN STUDY

The electrical machine was designed for use with an external combustion free piston engine, requiring a rated force capability of 800 N and connected to a resistive load. The specification of generator and engine can be seen in TABLE 1.

TABLE 1 . SPECIFICATION OF LINEAR ENGINE.

Specification	Value	Unit
Peak force of generator	≈ 800	N
Peak velocity	≈ 4.8	m/s
Moving mass	≤ 8.0	kg
Stroke amplitude	120	mm

TABLE 2 shows the results of a design study, which compares performance of the long and short translator generator models. The average output electrical power of the generator driven by the engine in the short and long translator generators when powering a resistive load of 5 Ohms is 2120 Watts and 1770 Watts respectively. In addition, the ratio of generated electrical power to generator cost is double in the short translator generator compared to long translator generator, however the ratio of generated electrical power to weight of generator is 22% larger in the long translator generator.

TABLE 2 . GENERATOR SPECIFICATION.

Parameter [unit]	**Configuration**	
	Short Translator/Long stator	Long Translator/Short Stator
Rated force [N]	800	800
Phase resistance [Ω]	0.728	0.364
Phase inductance [mH]	4.645	2.625
Stator outer diameter [mm]	180	180
Translator outer diameter [mm]	103	103
Active electromagnetic length [mm]	120	120
Air gap [mm]	1.5	1.5
Machine length [mm]	240	240
PM mass [Kg]	1.6	3.18
Piston assembly and translator moving mass[kg]	5.2	9
Total machine mass [kg]	37.13	24.4
Force/pm mass ratio[N/kg]	500	250
Generator cost [£]	288	446
Load [Ω]	5	5
avg generator electrical power, [W]	2120	1770
W/£	7.36	3.96
W/kg	57	73

IX. Comparison of Long and Short Translator Generators with Constant Velocity

A. Thrust force characteristics

Electromagnetic force of short and long translator generators found by FEA analysis under constant velocity is shown in Fig. 7 with equal interaction of electric and magnetic loading in both generators. It is clear that, both generators are capable of generating average electromagnetic force of 800 N to meet the capability of the linear engine requirement.

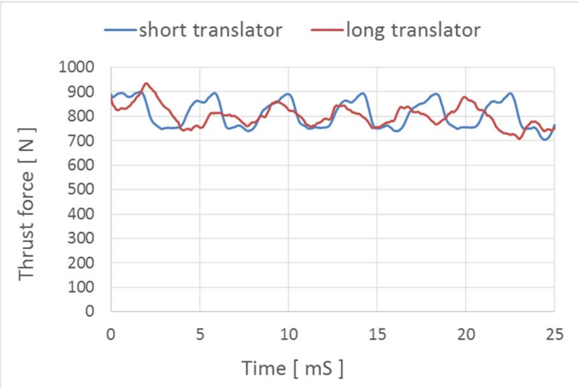

Fig. 7: Thrust force obtained by FEA analysis with constant speed of 4.8 m/s.

B. Resistive load characteristics

The linear electrical machine is operated as a generator, thus electrical current is drawn from generator to the load through continuous oscillation of the piston-translator assembly.

Electrical power versus resistive load characteristic of the two generator configurations can be seen in Fig. 8. In MagNet software, for FEA analysis, applied velocity to the translator is kept constant for both generator configurations regardless of the mass of translator 4.8 m/s.

Initial conclusion found by FEA, shown in Fig. 8, is that, the longer translator design produces double the amount of electrical power compared to short translator - due to the value of internal impedance being halved as shown in TABLE 2, this is because in the short translator design half of the coils are inactive at any instance of time, yet they still carry current. The efficiency of the short translator/long stator configuration can be reached to long translator/short stator configuration by employing an active rectifier to stop current flowing through inactive coils.

For a better comparison, performance when connected to the linear engine is required rather than just only electrical machine design under assumed constant velocity.

This ignores any change in the engine's performance resulting from the change in translator mass.

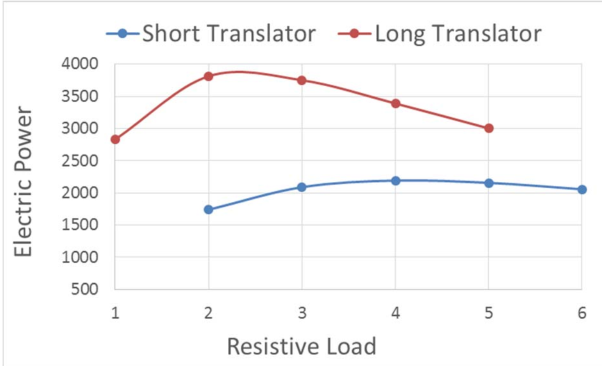

Fig. 8: Electrical power versus resistive load FEA, constant velocity of 4.8 m/s.

X. Comparison of Long and Short Translator Generators with Variable Velocity

A. Dynamic simulation

When it comes to dynamic system performance, the engine acts as a prime mover and it provides a mechanical input power to generator. With the assumption that the input force from engine to generator is constant then the velocity is dependent on the mass of translator. As a result, the generator with lighter translator mass can work more efficiently than one with a heavier translator mass. This case study will be investigated in an advanced simulation model with modelling the dynamic of engine and generator in order to reveal the importance of optimal moving mass for electrical power generation.

B. No electrical load characteristics

In this case study the engine is connected to the generator which is in the open circuit condition in order to look at the ripple force of the electrical machine. This ripple force is due to non-uniformity of reluctance path in the air gap area (slot effects) and oversizing of translator or stator (end effects) as well as velocity effect/core loss (iron loss & eddy current loss). Thrust force with current equal to zero Amps for the long and short translator generator designs when coupled to the full thermodynamic model can be seen in Fig. 9.

It should be noted that, the differences in characteristics can be attributed to the change in end effects for the two machines and the thermodynamic reaction to changing the translator mass.

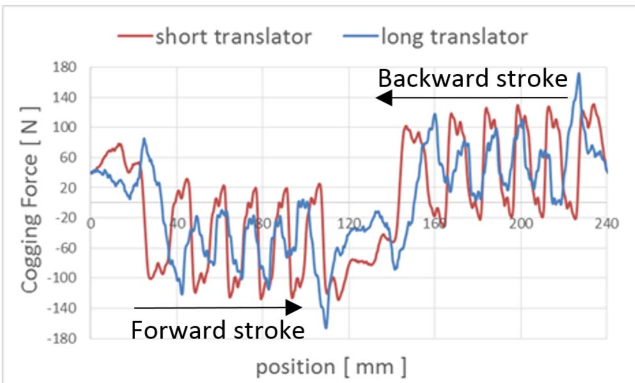

Fig. 9: Cogging force of short and long translator generators versus time for one full mechanical cycle.

C. Dynamic resistive load characteristics

Electrical power generation versus resistive load in FPEG system is shown in Fig. 10. It can be seen that, short translator generator can generate about 15 % more electric power compared to long translator generator when both generators are connected to resistive load of 5 Ohms, see TABLE 2.While by increasing resistive load, this differences between electrical powers of both generators increase to about 32 % with the resistive load of 15 Ohms. In other words, FPEG system with short translator can generate 32 % more electric power compare to FPEG system with long translator. This is a direct result of the short translator generator having a lower mass, hence it reciprocates faster than long translator generator, see Fig. 11.

The final conclusion found by dynamic system simulation shows in Fig. 10 that, unlike the initial results found by FEA, short translator generator is better for electrical power generation in FPEG system application. In addition, velocity profile of moving mass of long and short translator generator in FPEG system is shown in Fig. 11 which reveals that, short translator generator reciprocates faster than long translator generator.

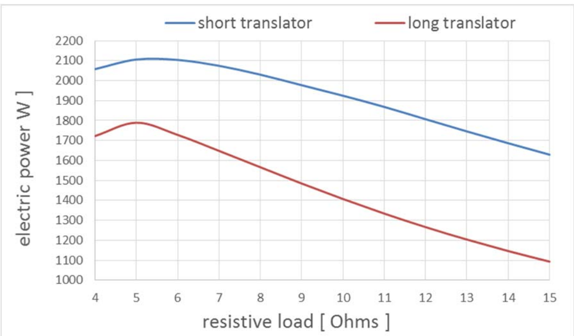

Fig. 10: Electrical power versus resistive load under dynamic system performance with variable velocity.

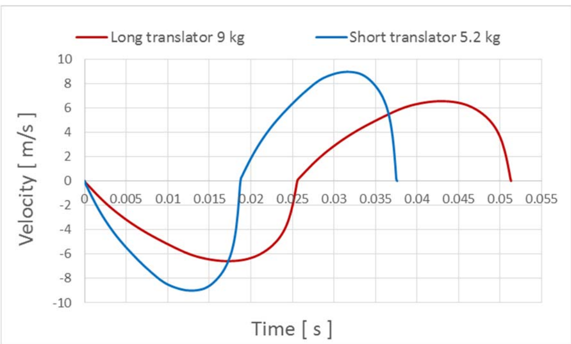

Fig. 11: Velocity profile of moving mass of long and short translator generator in FPEG system.

XI. CONCLUSION

This paper described and compared the performance of two generator configurations for electrical power generation. Initial conclusion was that long translator generator is capable to generate more power compared to short translator generator without considering the engine driving force, however when both generators are connected to the linear engine, the generator with shorter translator generates more electrical power due to having lighter moving mass, hence the translator reciprocates faster, hence more back emf and electrical power can be extracted.

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